

Laws of heat radiation from spherical gas volumes.

Part II. Modeling of heat radiation from volume bodies by radiation from spherical and cylindrical gas volumes

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Abstract—The results stemming from mathematical modeling of radiation from gas volumes of torches of furnaces, fire boxes, combustion chambers by spherical and cylindrical gas volumes are presented. The calculation results in the simulation of torches by cylindrical and spherical gas volumes differ by 0,4-2,3%. The calculation of radiation fluxes from torch on a heated product and burner throat in changing the length of the torch is performed, the results from the calculation are given.

The density of radiation flux from torch on the burner throat and the burner increases with decreasing the torch length. The calculation results are confirmed by experimental data. Using the laws of radiation from cylindrical and spherical gas volumes, the laws of Makarov and method for calculation heat transfer in furnaces, fire boxes, combustion chambers, developed on their basis, allow to improve exploited and projected flares, improve capacity utilization of fuel in furnaces from 20-45% to 55 -65%, reduce fuel consumption in many countries, development pressure on the environment.

Keywords— Scientific Disclosure, Laws, Heat radiation, Torch, Fuel Use Efficiency.

I. INTRODUCTION

The laws of heat radiation from isochoric isothermal concentric spherical gas volumes, which are called Makarov's laws for the purpose of adhering to centuries-old traditions of science and copyright. According to these laws: "The average beams from quadrillions of radiating particles of each isochoric isothermal concentric spherical gas volume to the calculated area equal to the distance from the center of the sphere to the calculated area and angular radiation coefficients, radiation flux densities from are equal.

Heat radiation flux density of the central spherical gas volume of a small diameter equal to the total power, radiated in all concentric spherical gas volumes to the calculated area. "

The volume model of the atom presents the nucleus in the form of spherical volume and electrons, which orbit in a concentric with nucleus spherical paths. Therefore, gas volumes, the torches of any complex shape can be filled with the spherical gas volumes of small and infinitely small diameter and their heat radiation can be calculated with high precision. Let us model the radiation from the part of torch that represents isothermal volume of rectangular parallelepiped [1.2], spherical and cylindrical gas volumes.

II. MATHEMATICAL MODELING OF HEAT RADIATION FROM GAS VOLUME

2.1. Mathematical modeling of heat radiation from gas volume by the radiation from cylindrical and spherical gas volumes.

Consider the radiation from the part of torch volume, that represents isothermal gas volume 1 in the form of rectangular parallelepiped of $a \times b \times h = 3 \times 3 \times 3$ meter [1.2] on the calculated area dF of the area $F = 0,5 \times 0,5 = 0,25$ m² (Fig. 1).

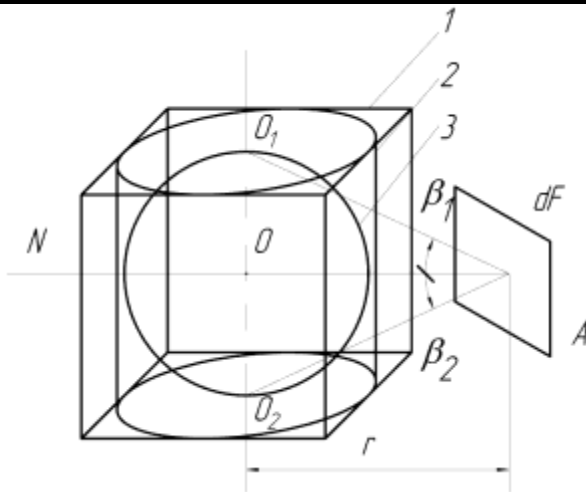


Fig.1: Modeling of heat radiation from gas volume in the form of rectangular parallelepiped by the radiation from cylindrical and spherical volumes.

Inscribe cylinder gas volume 2 of diameter 3 m, height $l_2 = 3$ m and spherical gas volume 3, 3 m in diameter in the rectangular parallelepiped 1.

Each of 1-3 gas emits $15 \cdot 10^{15}$ atoms at the same time, uniformly filling the volumes.

Perpendicular N, dropped to the center A of the area dF passes through the center of the symmetry O of the sphere 3 and the symmetry axis of cylinder gas volume 2 and bisects the symmetry axis O_1O_2 of the rectangular parallelepiped 1 and the cylinder 2 between their upper and lower bases.

The distance between the point O and the center of area symmetry dF is $r = 3$ m. Fig. 1 shows the following notation of angles: $\angle O_1AO = \beta_1$, $\angle O_2AO = \beta_2$, $\beta_1 + \beta_2 = \beta$. Each of the radiating gas volume releases equal radiation power $P_1 = P_2 = P_3 = 42$ MW, the absorption coefficient of the gas medium $k = 0.162$ [2].

The density of heat radiation flux incident on the calculated area dF from radiating cylindrical gas volume 2 is determined by the expression [2]:

$$q_{2dF} = \varphi_{2dF} P_2 F^{-1} e^{-kl_2} = \frac{FP_2 e^{-kl_2}}{F^2 \pi^2 l_y} \left[\beta + \sin \beta \cos(\beta_1 - \beta_2) \right] = \dots (1)$$

$$= \frac{0,2542 \cdot 10^3 \cdot e^{-0,1623 \cdot 11}}{0,2523 \cdot 14^2 \cdot 33} \left[\frac{52}{57} + \sin 52^\circ \cos 0^\circ \right] = 217,1 \text{ kW/m}^2$$

The first part of this article addresses the calculation of heat radiation flux density incident on the calculated area dF from spherical gas volume:

$$q_{3dF} = \varphi_{3dF} P_3 F^{-1} e^{-kl_3} = \frac{0,0022 \cdot 42 \cdot 10^3 \cdot e^{-0,162 \cdot 3}}{0,25} = 228,3 \text{ kW/m}^2 \quad (2)$$

In the process of calculation of heat radiation fluxes incident on the calculated area dF from cylindrical and spherical gas volumes, we obtained the results, that differ by no more than 5%. The difference Δ in the results of the calculations we determine by the expression:

$$\Delta = \left(1 - \frac{q_{2dF}}{q_{3dF}} \right) \cdot 100 = \left(1 - \frac{217,1}{228,3} \right) \cdot 100 = 4,9\% \quad (3)$$

Calculation accuracy of heat radiation flux density incident on the calculated area dF from gas volume in the form of a rectangular parallelepiped can be improved, provided that several tens of spherical gas volumes would be inscribed in it.

2.2. Mathematical modeling of heat radiation from gas volume by radiation of 216 spherical gas volumes.

Inscribe uniformly spherical gas volumes of 0.5 m diameter into the gas volume in the form of a rectangular parallelepiped (Fig. 2).

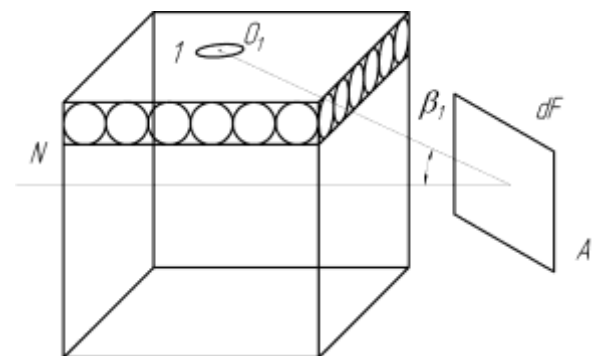


Fig. 2. Modeling of heat radiation from gas volume by 216 spherical gas volumes.

$$P_1 = P_2 = P_3 = \dots = P_{216} = 42 \cdot 10^3 / 216 = 194,4 \text{ kW}.$$

Inscribe 6 rows of spheres along the height of parallelepiped, 36 spheres in each row, 216 spheres in total (Fig. 2). Each of 216 spherical

releases the radiation power equal to $P_1 = P_2 = P_3 = \dots = P_{216} = 42 \cdot 10^3 / 216 = 194,4 \text{ kW}$.

In [3] it is derived a generalized analytical expression for calculating elementary angular coefficient of radiation from sphere of a small diameter to any calculated area, arbitrarily located in space.

For example, the formula for calculating the elementary angular coefficient of radiation from spherical gas volume 1, located in the center of the top row of the spheres

inscribed in parallelepiped on the area (Figure 2) has the form [3]:

$$\varphi_{1dF} = \frac{F \cos \beta_1}{4\pi l^2}, \quad (4)$$

where $\angle OAN = \beta_1$ is the angle between the perpendicular to the area dF and the ray OA , connecting the center of the area and the sphere 1; $AO = l$ is the distance between the center of the area dF and the sphere 1; F is the area of the platform dF .

Since, according to the law of Makarov, the elementary angular coefficients of radiation from isochoric isothermal concentric spherical gas volumes are equal, then using the expression (4), we can calculate the angular radiation coefficients of spherical radiation sources of infinitely small diameter on the calculated area as well as spherical giant radiation sources, such as heavenly stars, stars.

In the future, during long space flights, it will be important to know how far a spacecraft can move closer to the star without the risk of thermal destruction. The disclosed laws allow to calculate the heat fluxes incident on the hulk from the star at any distance to it, and the spatial position of the ship.

We determine the elementary angular coefficient of radiation from spherical gas volume of 1 on the calculated area dF (Figure 2.)

$$\varphi_{1dF} = \frac{F \cos \beta_1}{4\pi l_1^2} = \frac{0,25 \cdot \cos 18^\circ}{4 \cdot 3,14 \cdot 3,2^2} = 0,0018 \quad (5)$$

The density of heat radiation flux incident on the calculated area dF from the spherical gas volume 1 we determine by the expression:

$$q_{1dF} = \varphi_{1dF} P_1 F_1^{-1} e^{-kl_1} = \frac{0,0018 \cdot 194,4}{0,25 \cdot e^{0,162 \cdot 3,2}} = 0,833 \text{ kW/m}^2 \quad (6)$$

Similarly,

we define the densities of heat radiation fluxes incident on the calculated area dF from each of the 216 spherical gas volumes that fill a rectangular parallelepiped.

To automate the calculations, we used the program for calculating the angular coefficients of radiation and the radiation flux densities on a computer.

The total density of radiation fluxes $q_{\Sigma 216}$, incident on the area dF from 216 spherical gas volumes is determined by summing the radiation flux densities from 216 spherical gas volumes.

$$q_{\Sigma 216} = \sum_{i=1}^{216} q_{idF} = 212,2 \text{ kW/m}^2 \quad (7)$$

Compare

the results from (1), (2), (7) of modeling heat radiation from gas volume in the form of rectangular

parallelepiped by cylinder (1), spherical (2) gas volumes and 216 spherical gas volumes (7).

The most accurate results is presented in (7), as 216 inscribed spherical gas volumes fulfill the volume of a rectangular parallelepiped.

Calculation results from modeling heat radiation of gas volume in the form of rectangular parallelepiped by cylindrical gas volume have an error $\Delta_{\text{cyl}} = (1-212,2 / 217,1) \cdot 100 = 2,3\%$, a spherical gas volume $\Delta_1 = (1-212,2 / 228,3) \cdot 100 = 7,1\%$.

Thus, the heat radiation from gas volume in the form of rectangular parallelepiped can be modeled by the radiation from cylindrical gas volume inscribed in it, as the calculation error does not exceed 3%.

Heat radiation from gas volume in the form of a rectangular parallelepiped is not recommended to model by spherical gas volume inscribed in it since calculation errors exceed 7%.

The smallest error in the results of calculations from the true value of heat radiation density from gas volume in the form of a rectangular parallelepiped on the calculated area is achieved in modeling the radiation of parallelepiped by a few dozen spherical gas volumes inscribed in it.

To increase the number of inscribed in rectangular parallelepiped spherical gas volumes up to several hundreds or thousands of spheres is inappropriate, as this increases the number of computing operations, and the accuracy of calculations increases by tenths of a percent, namely (0,1- 0,8)% in comparison with the actual value of the radiation flux.

The preceding is confirmed by the following calculations confirm.

2.3. Mathematical modeling of heat radiation from gas volume by radiation of 15, 108, 432 spherical gas volumes.

Inscribe 15 spherical gas volumes 1 m in diameter each in a rectangular-parallelepiped gas volume in three rows I-III along the height and of 5 spherical gas volumes each (Fig. 3).

$$q_{2dF} = \frac{P_2 \cos \beta_2}{4\pi l_2^2} e^{-kl_2} = \frac{2,8 \cdot 10^3 \cdot \cos 40^\circ}{4 \cdot 3,14 \cdot 3,8^2} e^{-0,162 \cdot 3,8} \dots (8)$$

$$= 6,4 \text{ kW/m}^2$$

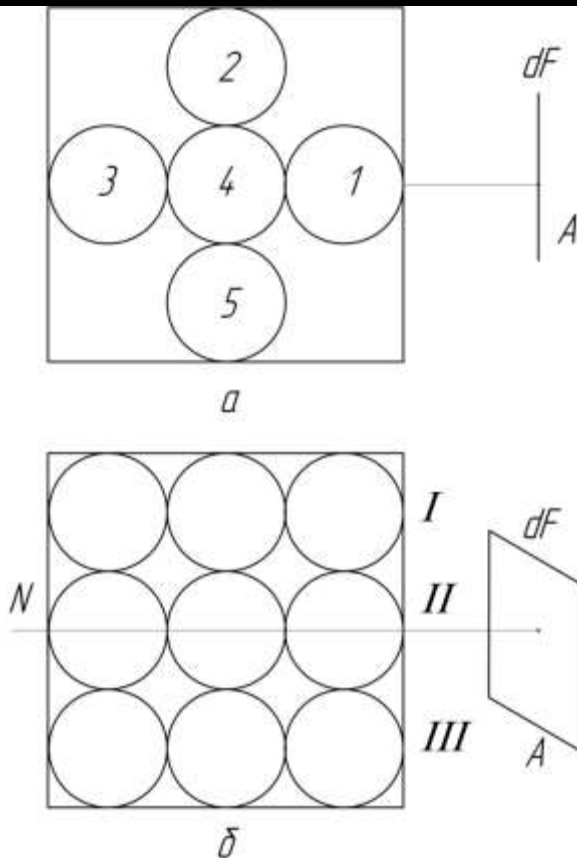


Fig.3: Modeling of heat radiation from gas volume by 15 spheres of gas volume, a - top view; b - front view. Each of the 15 spherical gas volumes radiate an equal radiation power $P_1=P_2=P_3=...=P_{15}=42 \cdot 103/15=2.8$ MW.

We denote by 1-5 spherical gas volumes of the first row. Substituting (4) into (6), we will calculate heat radiation flux densities incident on the calculated area dF from spherical gas volumes 1-3 (Fig. 3):

$$q_{1dF} = \frac{P_1 \cos \beta_1}{4\pi r_1^2} e^{-k_1 r_1} = \frac{2.8 \cdot 10^3 \cdot \cos 27^\circ}{4 \cdot 3.14 \cdot 2.2^2} e^{-0.162 \cdot 2.2} = 28.7 \text{ kW/m}^2 \quad \dots (9)$$

Similarly, we determine heat radiation flux densities incident on the calculated area dF from 4-15 spherical gas volumes.

By eq. (7) we determine the total radiation flux density from 1-15 spherical gas volumes on the calculated area dF :

Calculated area dF :

$$q_{3dF} = \frac{P_3 \cos \beta_3}{4\pi r_3^2} e^{-k_3 r_3} = \frac{2.8 \cdot 10^3 \cdot \cos 14^\circ}{4 \cdot 3.14 \cdot 4.2^2} e^{-0.162 \cdot 4.2} = 6.22 \text{ kW/m}^2$$

...(10)

$$q_{\Sigma 15} = \sum_{i=1}^{15} q_{idF} = 207.5 \text{ kW/m}^2 \quad \dots (8)$$

Calculate the error of calculation in modeling of heat radiation from gas volume in the form of rectangular parallelepiped by 15 spherical gas volumes: $\Delta 15 = (1 - 207.5 / 212.2) \cdot 100 = 2.2\%$.

Similarly, we modeled heat radiation from rectangular parallelepiped by 108 and 432 spherical gas volumes. As a result of calculations, we obtained the following values of total radiation flux densities incident on the calculated area dF from spherical gas volumes:

$$q_{\Sigma 432} = \sum_{i=1}^{432} q_{idF} = 213.1 \text{ kW/m}^2 \quad (12)$$

$$q_{\Sigma 108} = \sum_{i=1}^{108} q_{idF} = 210.3 \text{ kW/m}^2 \quad (13)$$

Miscalculation in modeling heat radiation from gas volumes in the form of parallelepiped by 108 and 432 spherical gas volumes equal to, respectively: $\Delta 108 = (1 - 210.3 / 212.2) \cdot 100 = 0.9\%$, $\Delta 432 = (1 - 212.2 / 213.1) \cdot 100 = 0.4\%$.

Miscalculation in modeling heat radiation from gas volume in the form of parallelepiped by one cylindrical gas volume is 2.3%, one spherical gas volume is 7.1%, 15 spherical gas volumes is 2.2%, 108 spherical gas volumes is 0.9%, 432 spherical gas volumes is 0.4%.

Thus, gas volume in the form of parallelepiped can be modeled by cylindrical gas volume, one-two hundred spherical gas volumes and obtain the results from calculations with high accuracy.

III. CALCULATIONS OF HEAT RADIATION FROM THE TORCH ON THE HEATING SURFACES

3.1. Calculation of heat radiation from torch on the surface of products and burner throat.

The torch is used in heating furnaces, fire boxes, steam boiler boxes and combustion chambers of gas-turbine power plants[1-4].

Torch, created by a single burner, is an ellipsoid of revolution, which burns the fuel, supplied to the burner [1-4]. Torch length is the distance from the burner, at which at least 98% of the fuel is burnt. To calculate heat radiation from torch on the heating surfaces, it is necessary to solve triple integral equations, describing volume radiation from torch. In the 20th century the

solution for triple integral equations in the form of analytical expressions, formulas was not found [1].

However, the disclosure in the late 20th century of the laws for heat radiation from cylindrical and spherical gas volumes, laws of Makarov and the methods for calculation, developed on their basis, allow to simulate the torch by a set of cylindrical and spherical gas volumes and calculate the fluxes of the heat radiation incident on the heating surface from the torch [1- 4].

The developed method of heat transfer in torch furnaces allows to calculate the rational fuel consumption, the location of the burners and the rational parameters of the torch: length, power and its distribution over the length, the spatial position in the furnace, the angle of torch. We use the results from analytical studies to calculate the torch radiation fluxes incident on the heating surfaces in the torch furnace.

Investigate the effect of torch length on the distribution of heat radiation fluxes along the heating surface.

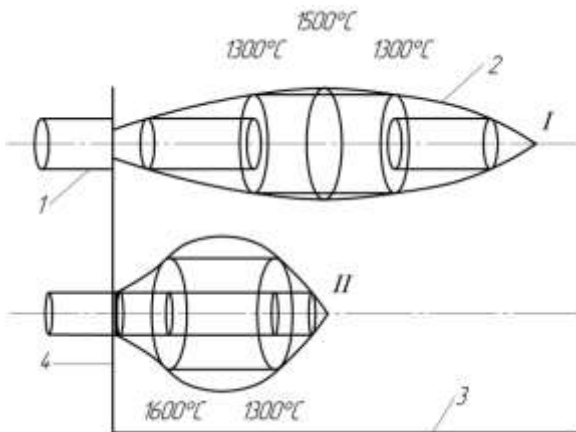


Fig. 4: Location of the torch in the furnace.

Fig. 4 shows a portion of the working space of the heating furnace and we used the following notations: 1 - burner; 2 - torches I and II; 3 - the horizontal surface of the heated product; 4 - the vertical lined wall of furnace with burner throat.

Burners are located in the wall embrasures. Torch length I $l_{t1} = 8\text{m}$, torch length II $l_{t2} = 3\text{m}$, torches power is the same and equal to 5 MW.

The axes of the torches I and II are in the same vertical plane with the axis of symmetry of the product and parallel to the horizontal surface of the product 3 and removed from it at a distance of 0.8m.

In order for torches I and II to not combine torches into one, Fig. 4 uses a different scale of their location on the vertical wall 4.

In accordance with the location of isotherm of 1300, 1500 °C, the torch I is modeled by four cylinder gas volumes, the torch II is simulated by three cylindrical gas volumes in calculations.

According to the method, described in [2-4], as well as in the first part of the monograph, we calculated heat radiation flux densities of torches I and II incident on the horizontal surface along the length of the product l_p and vertical surface along the height of embrasures H_e . The calculation results are shown in Fig. 5.

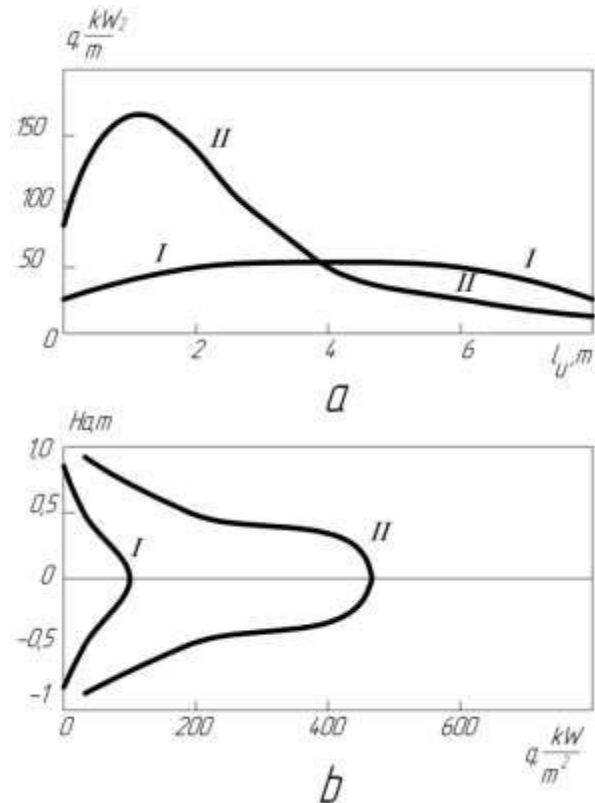


Fig.5: The distribution of the heat fluxes from the torch along the horizontal surface (a) and embrasure surface (b).

As can be seen from the results of calculations, the distribution of the heat radiation flux densities from the torches depends heavily on their geometric dimensions: length and expansion angle.

The distribution of heat radiation fluxes incident on the surface of the product from the torch I 8 m in length is uniform: 28 kW/m² is on the periphery, 57 kW/m² is in the center.

With the decrease of the torch length at its constant capacity, the densities of radiation fluxes on the product regions, located near the walls and burner throat increase 2-3 times, and decrease 3-5 times on the regions distant from the burner throat.

With the length of the torch 3m, the torch radiation flux densities on the product is 165 kW/m² at a distance of 1m from the vertical wall, at a distance of 8 meters from a vertical wall is 5 kW/m².

Radiation flux densities incident on the burner throat and the burner increase with the changes in the torch length. With the torch length of 8m and 3m, the flux density

incident on the burner throat and the burner along its is 78 kW / m² and 520 kW / m², respectively and decreases sharply along the height of the burner throat.

The calculation results are confirmed by experimental data [5,6]. The long experience of operation of steam boilers TGMP-314TS with cyclone burners of 50-60MW at power plants CHP-21, Mosenergo CHP-23, Konakovo DWP and other power plants with short torches deepened in the burner throat showed frequent burnout of burners, refractories destruction of burner throat, that is connected with large fluxes of heat radiation from the torch on the burner throats and burners.

After the reconstruction of boilers, installation of gas-oil burners and increase the torch length 2 times, the service life of the burners was increased from 1 year up to 5-10 years and more [5,6], that is connected with a decrease in heat fluxes from the torch on the burner, a decrease in the temperature of metal of the burners, refractories of the burner throat.

Similar results were obtained by the calculation. Thus, the results from the calculations are confirmed by the results of experimental studies of the effect of the torch length on the heating fluxes, thermo destruction and burners life [5,6].

3.2. Using the laws of heat radiation from cylindrical and spherical gas volumes in the practice of the operation and design of torch furnaces, combustion chambers.

Using the laws of heat radiation from cylindrical and spherical gas volumes, laws of Makarov and method for calculating heat transfer in torch furnaces, combustion chambers, developed on their basis, allow to improve the exploited and designed flares.

Torch furnaces is widely used in metallurgy and in all branches of industry: heavy, chemical, nuclear, energy, transport and other industries, as well as in glass, ceramic, porcelain industry, autoindustry.

Flare furnaces are used in these industries for heating products before plastic deformation (forging, stamping, pressing), heat treatment of products (hardening, annealing, tempering, carburizing, nitriding, normalizing, austenitizing) and drying products.

Flame box furnaces, single-stack furnaces, rotary-hearth furnaces, roller-hearth furnaces, tunnel-type furnaces, continuous furnaces, pusher-type furnaces with product-loading mass of 100kg to 120 tons with a burners capacity of 10kW to 50MW are used for heating and heating treatment of products.

In the 20th century due to the lack of triple solutions of integral equations, describing the volume radiation from the torch, parameters of torches and their location in the furnaces were determined largely experimentally on test

stands and operating furnaces, fire boxes, combustion chambers.

The operating and designed heating furnaces have short torches, often placed irrationally, far from the heated products. Torches are placed away from the heated products to cause no melting of products surface. Torches are placed so as to heat fire-resistant surfaces of walls, arch, hearth, and heated fire-resistant surfaces radiate heat flux on the products, heating them [4], however, such organization of heat transfer causes conductive heat losses through the walls, arch, hearth of the furnace.

It is assumed, that the products are heated by combustion products, gases leaving the torch and filling the working space of the furnace.

However, the calculations showed, that the proportion of the heat flow incident on the heating surface [4] from the combustion products is 5-7% of the total heat flux. As a result of such organization of heat transfer, fuel efficiency in torch furnaces is 25-45% at this time [7].

The use of scientific discovery and calculation methods, developed on its basis, allow to determine the following rational parameters of the torch, burners, and products. Rational position of products in the furnaces, the location of the burners, power, expansion angle, the length of the torches, the rational distribution of the torch fluxes densities on the heating surface wherein limit heat fluxes, causing melting of the surfaces of products are not exceeded.

In rational arrangement of the products and burners, the torches, the parameters of torches, fuel efficiency ratio in furnaces can be increased to 55-65%.

Torch of gas turbine combustion chambers has a complicated shape, which depends on the number of burners, swirlers, traffic organization of air, fuel, combustion products [3,8]. The camera has several active zones of fuel combustion, the torches of complex geometric form. Calculation of heat radiation fluxes of the torches on the flame tube, burner, swirlers is a complex scientific task.

Typically, the information of heat radiation fluxes on the heating surfaces of the combustion chamber is obtained by expensive testing of the combustion chamber on the test stands. Scientific discovery of laws of radiation from gas volumes allows to simulate the heat radiation from torches of combustion chambers by cylindrical and spherical gas volumes.

Mathematical modeling allows to calculate the heating and cooling flows of the combustion chamber at the design stage, to organize a rational heat transfer in the chamber, to decrease the testing time and the costs for camera testing on the stands [3].

Modeling steam boiler boxes by cylindrical gas volumes allows to calculate the distribution of radiation fluxes

density along the perimeter of furnace walls, distribute water-cooled surfaces of the torches burners by provided heat quantity and identify the most tense areas to determine the schedule of repairs, to reconstruct the furnaces in order to increase their efficiency [9,10].

Over the last century the use of the laws of radiation from solid bodies, the laws of Stefan-Boltzmann, Planck, Wien in the design of solid furnaces, fire boxes allow to increase fuel efficiency ratio in these plants from 25-30% at the beginning to 70-90% at the end of the 20th century. Similar processes are expected in the 21st century with the design of torch furnaces using the laws of radiation from gas volumes, Makarov's laws. Currently, fuel efficiency in torch furnaces is 25-45%. The use of the laws of radiation from gas volumes in design and calculation of laws of radiation from gas volumes allow to increase the fuel efficiency in torch furnaces from 25-45% to 55-65% in the coming decades.

IV. CONCLUSION

The new concept and method for calculating heat transfer in furnaces, fire boxes, and combustion chambers is developed. In accordance with them cylindrical and spherical radiating gas volumes from which the calculation of heat radiation fluxes on the heating surface is performed, inscribe in the torch.

Heating fluxes of the torch, heated surfaces, combustion products are calculated for heated surfaces, taking into account the reflection and absorption. The calculation error does not exceed 10%.

The new concept and method for calculation allow thousands of researchers and engineers in dozens of countries around the world to create new design of the heating and melting furnaces and power plants.

New constructions of torch furnaces, fire boxes, combustion chambers is expected to increase productivity, fuel efficiency, prolong the time between overhauls, reduce fuel rate, environmental impact.

The author together with his students developed three dozens of new designs of electric arc steel melting furnaces and the ways for steel melting in them [11], torch heating furnaces and the ways for product heating in them [12].

New designs of arc steel melting furnaces and torch furnaces are characterized by a decrease in electricity and fuel consumption, a raise in the productivity.

New designs of steam boiler boxes [9,10] and combustion chambers [13] are developed and characterized by the alignment of the heat flows on the heating surfaces, decrease in fuel consumption, increase in the time between overhauls [14].

REFERENCES

- [1] A.N. Makarov "Modeling of a Torch and Calculation of Heat Transfer in Furnaces, Fire Boxes, Combustion Chambers. Part I. Calculation of Radiation from Solids and Gas Volumes by the Laws of Radiation from", International Journal of Advanced Engineering Research and Science, Vol. 3, No 12, PP. 44-48, 2016, DOI: 10.22161/ijaers/3.12.9
- [2] A.N. Makarov "Modeling of a Torch and Calculation of Heat Transfer in Furnaces, Fire Boxes, Combustion Chambers. Part II. Calculation of Radiation from Gas Volumes by the Laws of Radiation from Cylinder Gas Volumes", International Journal of Advanced Engineering Research and Science, Vol. 3, No 12, PP. 49-54, 2016, DOI: 10.22161/ijaers/3.12.10
- [3] A.N. Makarov "Heat transfer in electric arc and torch metallurgy furnaces and energy plants: textbook", Lan', St-Petersburg, 384p., 2014
- [4] A.N. Makarov "Calculation of Heat Transfer in Torch Furnaces by Gas Volume Radiation Laws", World Journal of Engineering and Technology, No 4, pp. 488-503, 2016. DOI: 10.4236/wjet. 2016. 43049
- [5] A.N. Zroichikov, Yu.P. Enykin B.N. Glusker, I.V. Galas, V.V. Zypkin, N.A.Chuprov, V.A. Vereshagin «Modernization of boilers TGMF-314Z, equipped with cyclone predoplaty to reduce harmful emissions and improve the reliability of operation of burners and heating surfaces», Teploenergetika, No 12, pp.17-21, 2002.
- [6] K.V. Osintsev, "Method of reducing heat flow to the burner throats", Elektricheskie stancii No 11, pp.13-17, 2009.
- [7] A. M. Vohmykov, M. D. Kazyaev, B. N. Arseev, D. M. Kazyaev, A. I. Ryapov "Integrated modification of heating furnaces", Proceedings of the universities. Chernaya Metallurgiya, No 12, pp. 56-59, 2009.
- [8] G. G. Olkhovsky, "Thermal testing of stationary gas turbine plants", Energiya, Moscow, 406 p., 1971.
- [9] A.N. Makarov, M.N. Shevchenko. Furnace for reducing gas and fuel-oil / Patent for the invention No 2400668, Inventions, №27, 2010.
- [10] A.N. Makarov, F.N. Neverov, A.V. Kyznetsov. Furnace for oil-gas fuel burning / Patent for invention No 2547675. Inventions, №10, 2015.
- [11] A. N. Makarov, E. V. Kruglov, V. V. Rybakov. DC ASF // Patent for the invention №2516896, Inventions, No. 15, 2014
- [12] A.N. Makarov, E.V. Kruglov, V.V. Rybakova. Heating furnace with ring bottom/ Patent for invention №2517079. Inventions, No 15, 2014.
- [13] A.N. Makarov, A.V.Kuznetsov Combustion chambers of turbogas unit / Patent for the useful model No 157527, Inventions, No 34, 2015.

- [14] A.N. Makarov “Flare Temperature and NTitrogen Oxide Emission Reduction in the TGMP-314 I Steam Boiler Firebox”, Power Technology and Engineering, Vol. 50, №2, pp. 200-203, 2016. DOI: 10.1007/S10749-016-0683-x